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Energie nucléaire

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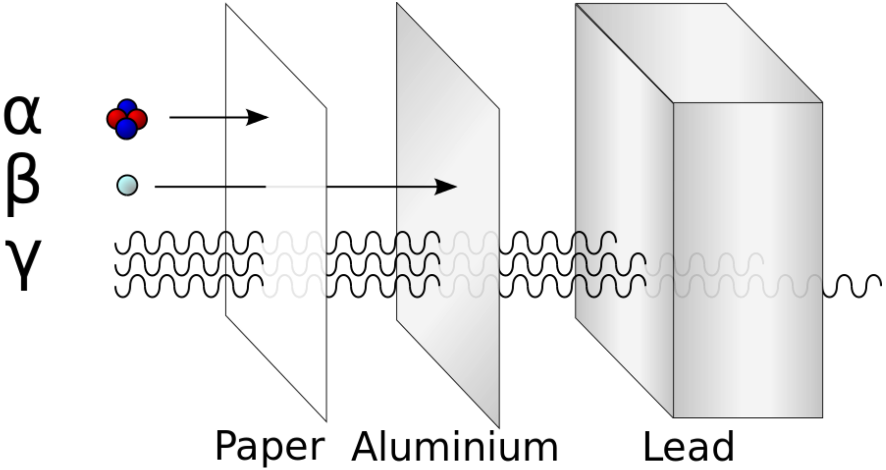
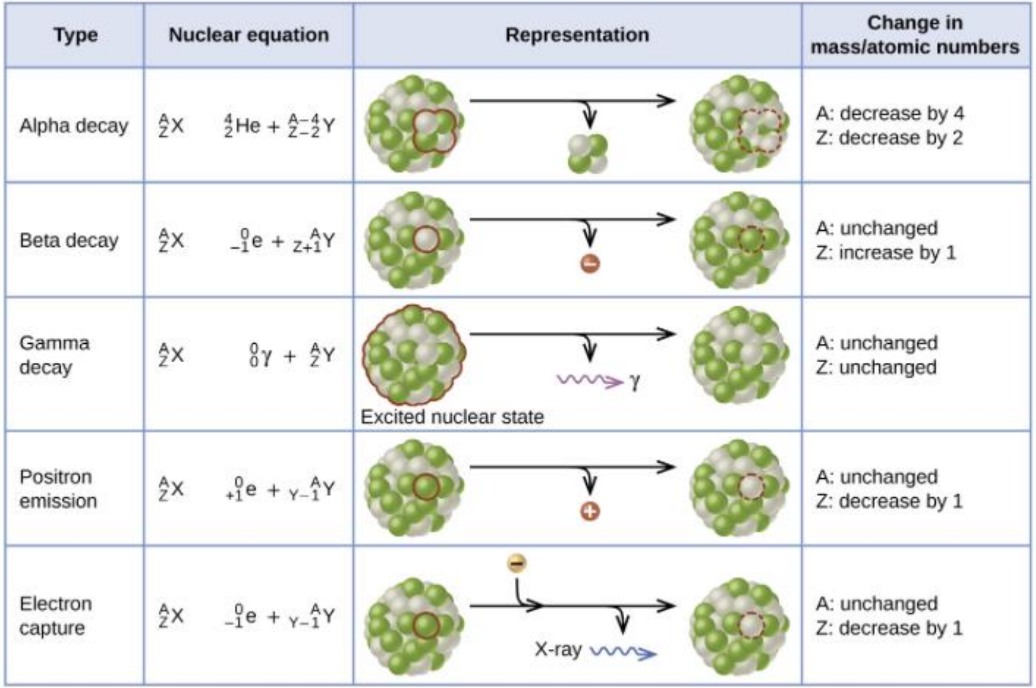
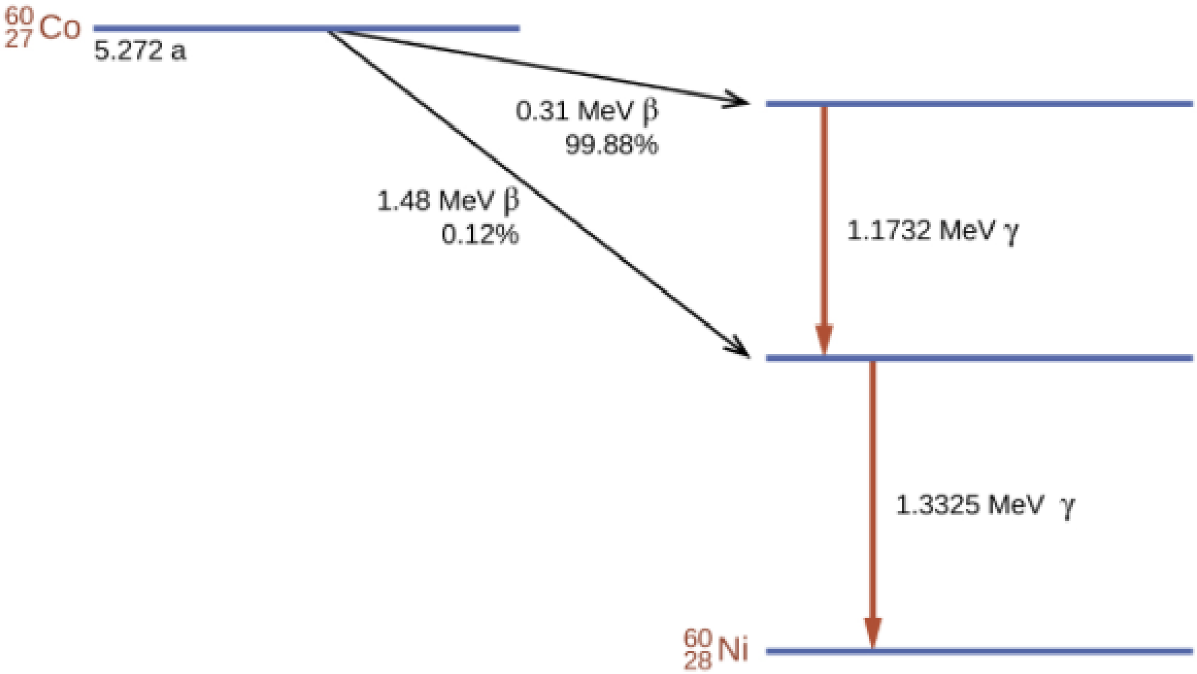
Agenda

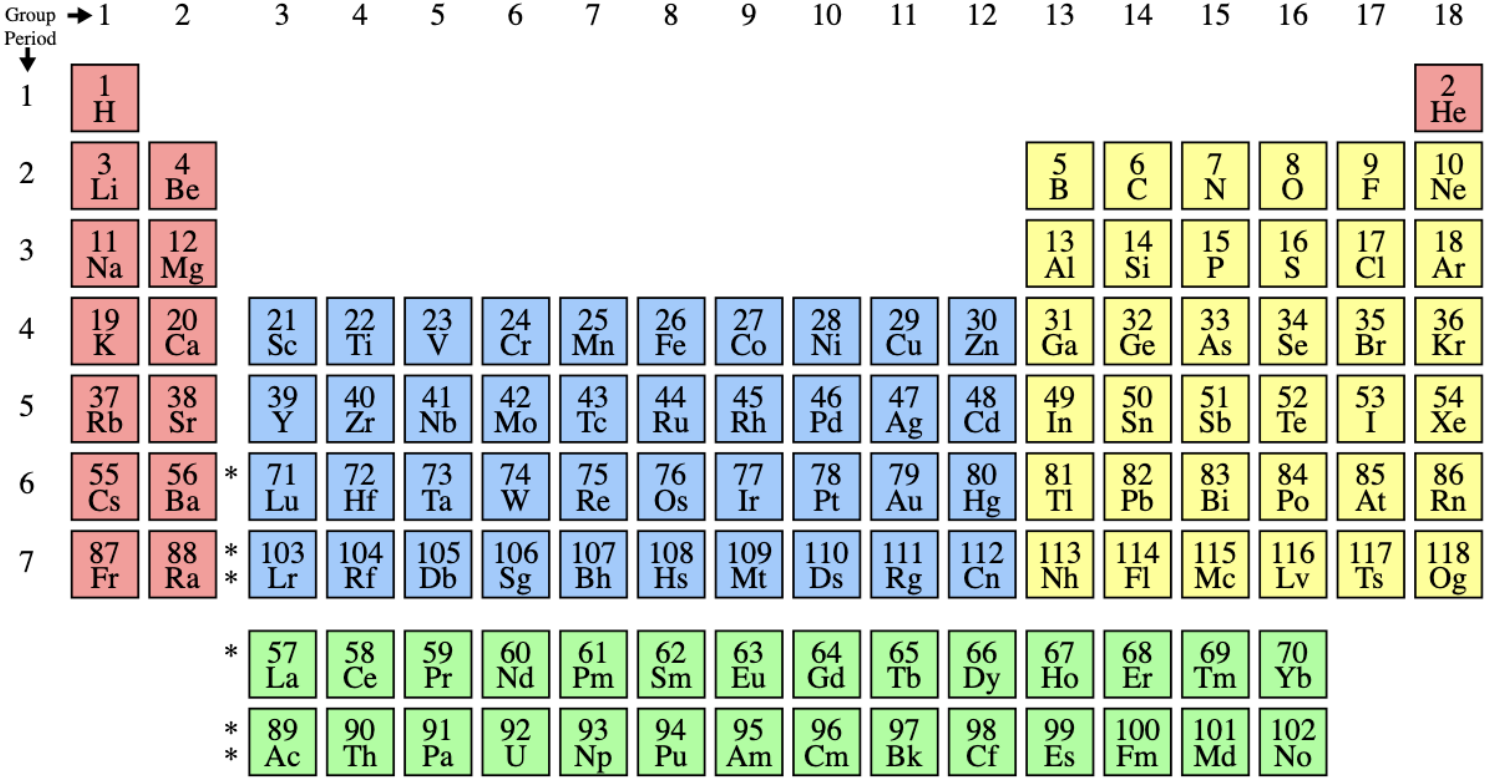
- 8:20 – 9:00h:
  - Introduction: La radioactivité (α,β,γ,n)
  - Les isotopes, la carte des nucléides,
  - L'origine des isotopes, l'Uranium
  - La fission, la réaction en chaine
  - Banane
- 9:00h – 9h45: Visite de CROCUS par Laurent Braun
- 9:45h – 10h15:
  - Energie nucléaire: Contexte suisse
  - Réacteur nucléaire: Fonctionnement
  - Modérateur: pourquoi?
- 10:15h – 12h00:
  - Expérience 'Approche critique': comment démarrer un réacteur
- 12h00:
  - Lunch


α
β
γ
Paper
Aluminium
Lead



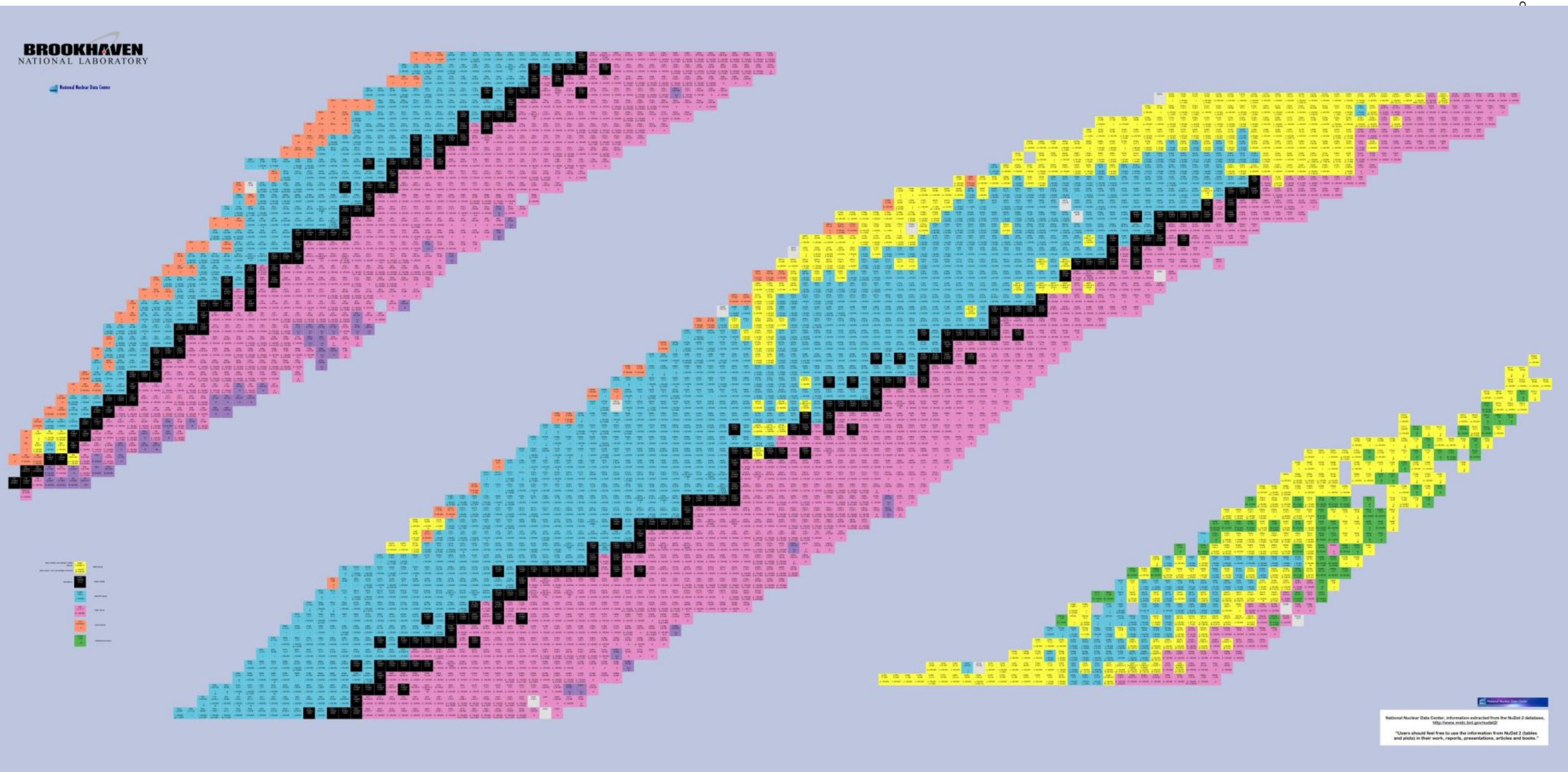
Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	$^{A}_{Z}\text{X}$ $\quad {}^{4}_{2}\text{He} + {}^{A-4}_{Z-2}\text{Y}$		A: decrease by 4 Z: decrease by 2
Beta decay	$^{A}_{Z}\text{X}$ $\quad {}^{0}_{-1}\text{e} + {}^{A}_{Z+1}\text{Y}$		A: unchanged Z: increase by 1
Gamma decay	$^{A}_{Z}\text{X}$ $\quad {}^{0}_{0}\gamma + {}^{A}_{Z}\text{Y}$	γ Excited nuclear state	A: unchanged Z: unchanged
Positron emission	$^{A}_{Z}\text{X}$ $\quad {}^{0}_{+1}\text{e} + {}^{A}_{Y-1}\text{Y}$		A: unchanged Z: decrease by 1
Electron capture	$^{A}_{Z}\text{X}$ $\quad {}^{0}_{-1}\text{e} + {}^{A}_{Y-1}\text{Y}$	X-ray	A: unchanged Z: decrease by 1


$^{60}_{27}$Co
5.272 a
0.31 MeV β
99.88%
1.48 MeV β
0.12%
1.1732 MeV γ
1.3325 MeV γ
$^{60}_{28}$Ni



Group → Period ↓	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	* *	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			* *	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

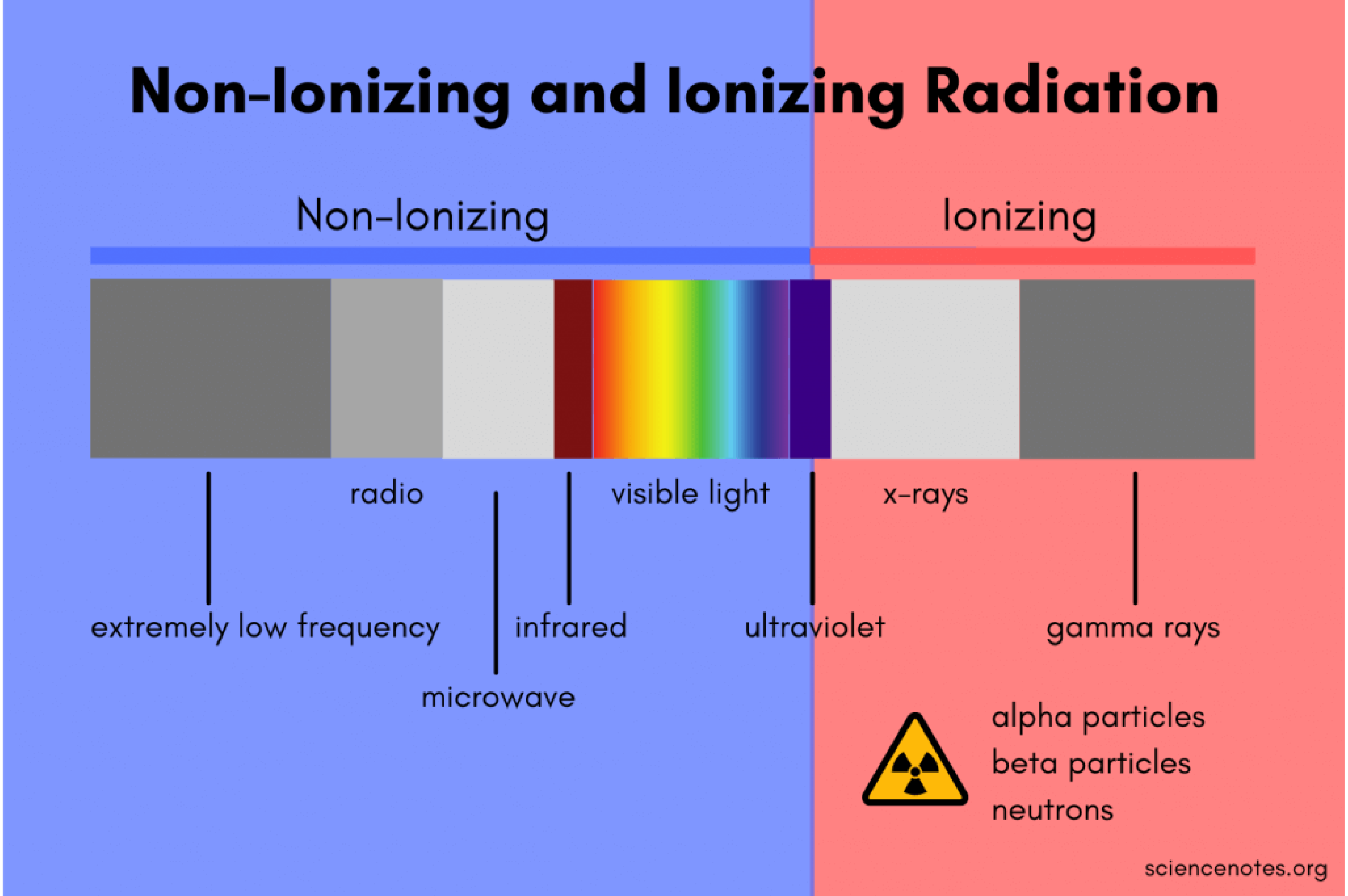
La carte des nucléides



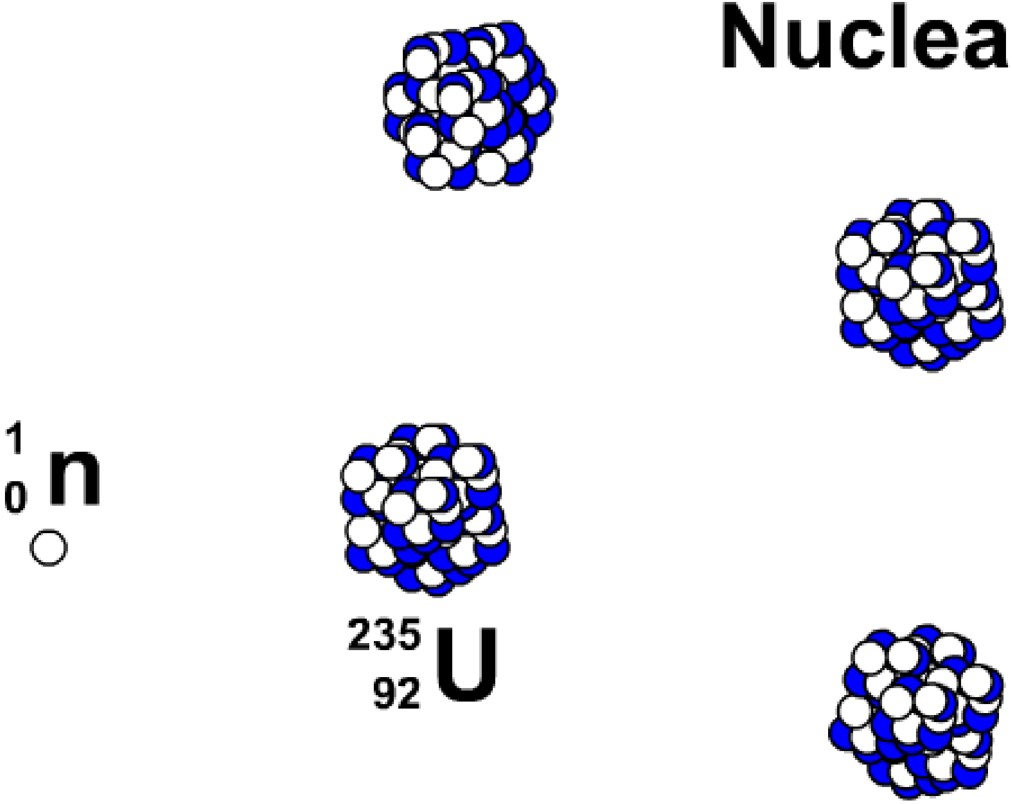
National Nuclear Data Center, information extracted from the NuDat 2 database, http://www.nndc.bnl.gov/nudat2/

"Users should feel free to use the information from NuDat 2 (tables and plots) in their work, reports, presentations, articles and books."

Non-Ionizing and Ionizing Radiation

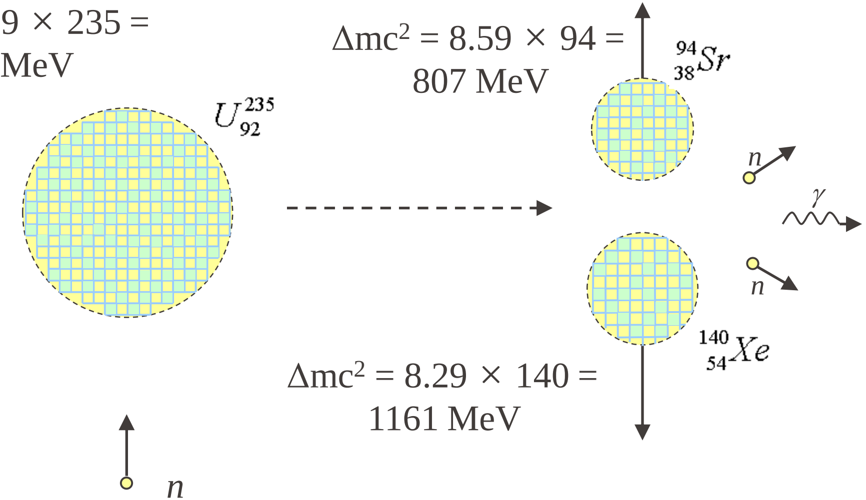


Nuclear Fission



$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{142}_{56}\mathrm{Ba} + {}^{91}_{36}\mathrm{Kr} + 3\left({}^{1}_{0}\mathrm{n}\right)$$

One of the possible fission reactions : $n+{}^{235}_{92}U\rightarrow{}^{140}_{54}Xe+{}^{94}_{38}Sr+2n$



$\Delta mc^2 = 7.59 \times 235 =$
1784 MeV

$\Delta mc^2 = 8.59 \times 94 =$
807 MeV

$\Delta mc^2 = 8.29 \times 140 =$
1161 MeV

mass defect		**mass defect**		**energy release**
–1784 MeV	=	–1968 MeV	+	184 MeV

Energy released is also called Q-value of the reaction

Pourquoi le nucléaire?– Fossile versus fissile

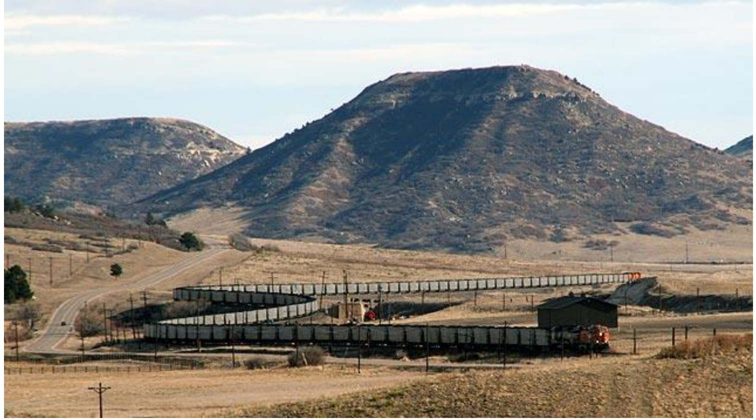
$$1eV = 1.6022 \times 10^{-19}\ \text{J}$$

$$\text{C} + \text{O}_2 \rightarrow \text{CO}_2 + 4\text{eV}$$

$$^{235}\text{U} + \text{n} \rightarrow 2\text{FPs} + 200 \times 10^6\,\text{eV}$$

1000 MWe centrale électrique:

~ 10 000 t de charbon (100-wagon train) **par jour**
~ 20 t de U combustible **par an**



< 1x par jour

THE POWER OF URANIUM

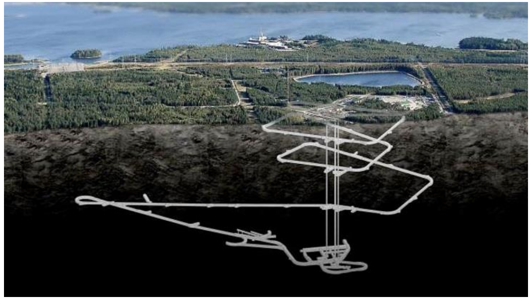
20 grams of
URANIUM

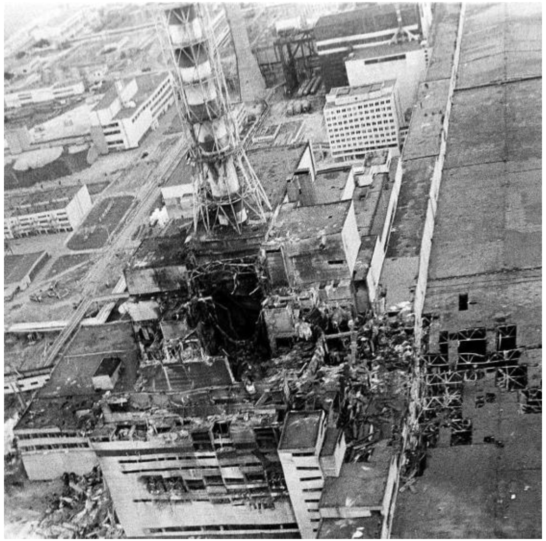
400 kilograms of
COAL

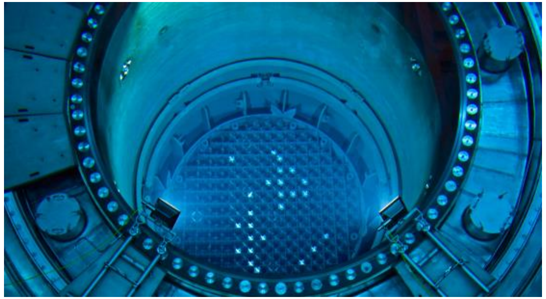
410 litres of
OIL

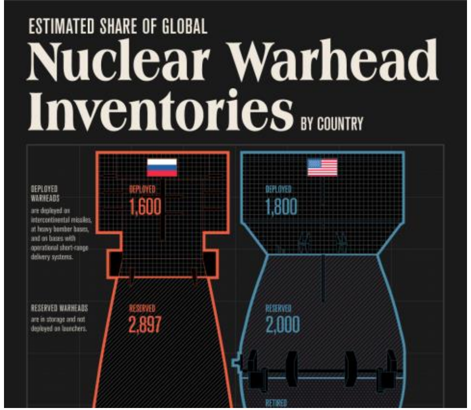
350 cubic metres of
NATURAL GAS

Pourquoi pas?



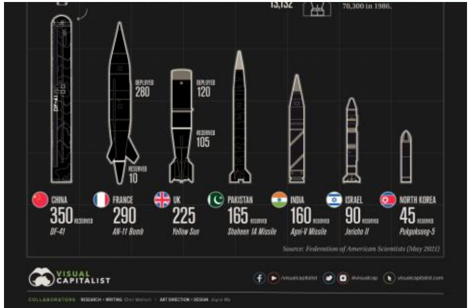




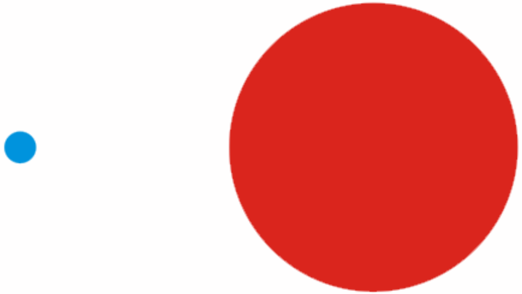


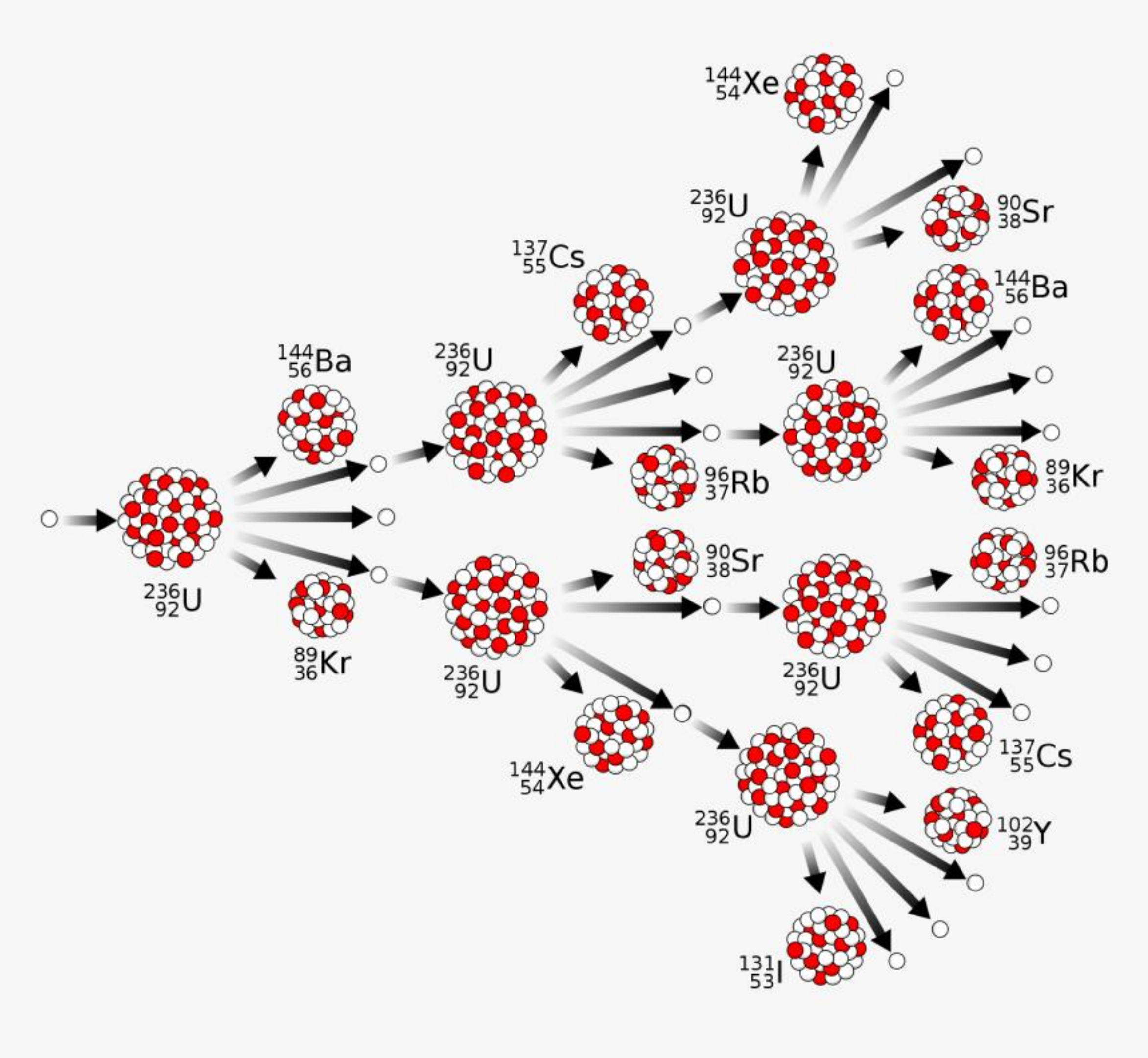
IAEA

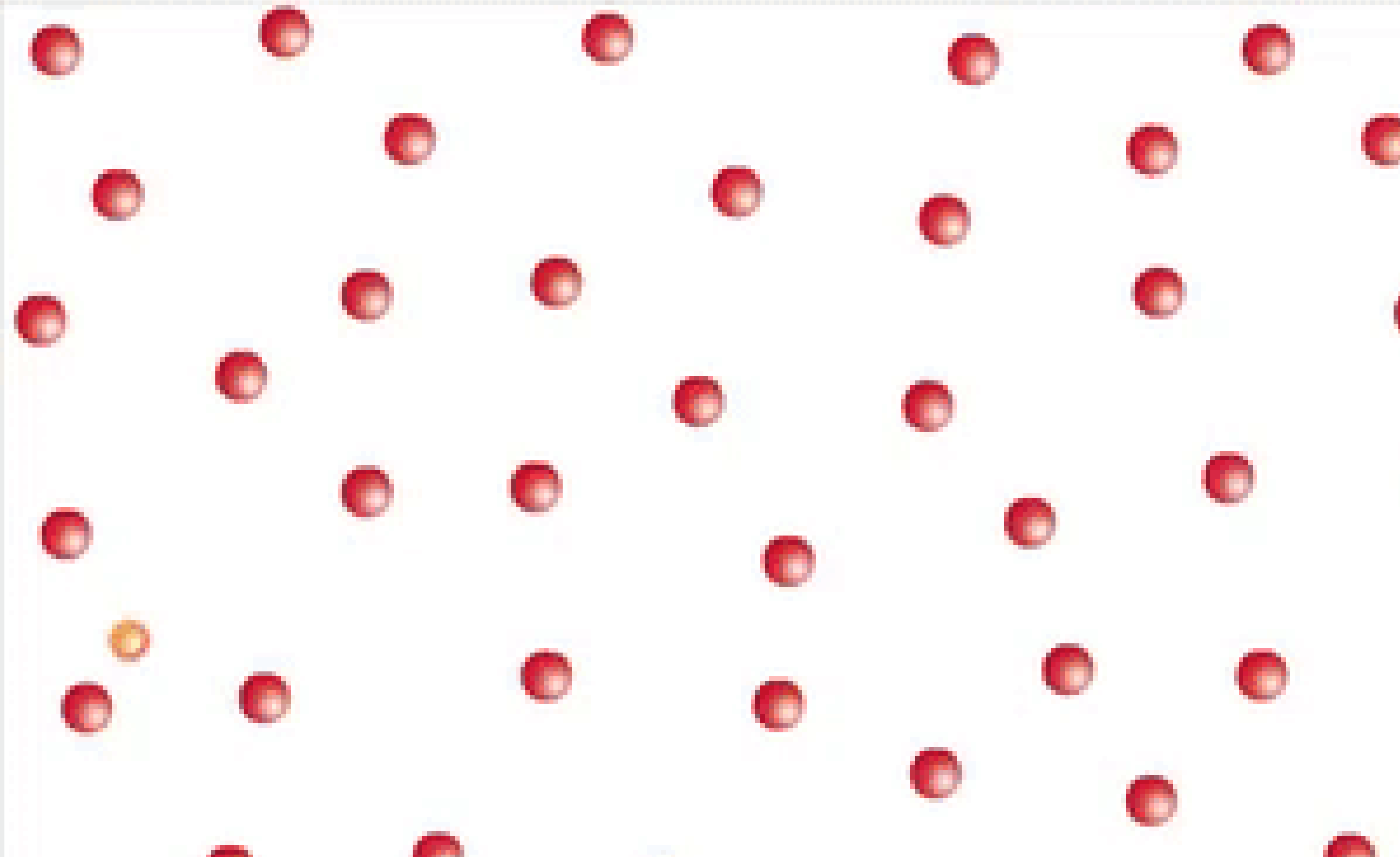
International Atomic Energy Agency



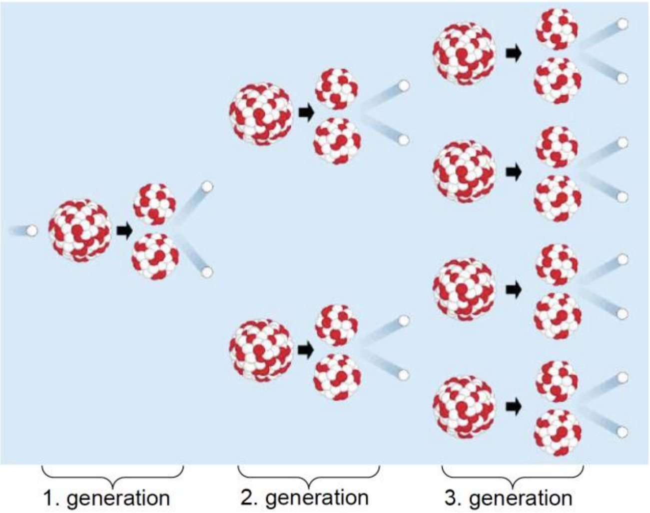
Source: Federation of American Scientists (May 2021)



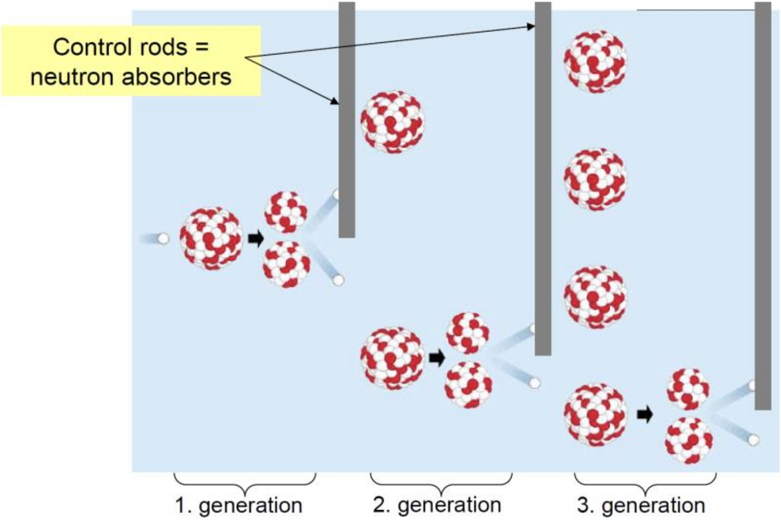

$^{236}_{92}U$
$^{144}_{56}Ba$
$^{89}_{36}Kr$
$^{236}_{92}U$
$^{236}_{92}U$
$^{137}_{55}Cs$
$^{96}_{37}Rb$
$^{90}_{38}Sr$
$^{144}_{54}Xe$
$^{236}_{92}U$
$^{236}_{92}U$
$^{236}_{92}U$
$^{236}_{92}U$
$^{144}_{54}Xe$
$^{90}_{38}Sr$
$^{144}_{56}Ba$
$^{89}_{36}Kr$
$^{96}_{37}Rb$
$^{137}_{55}Cs$
$^{102}_{39}Y$
$^{131}_{53}I$



Réaction en chaine sans contrôle

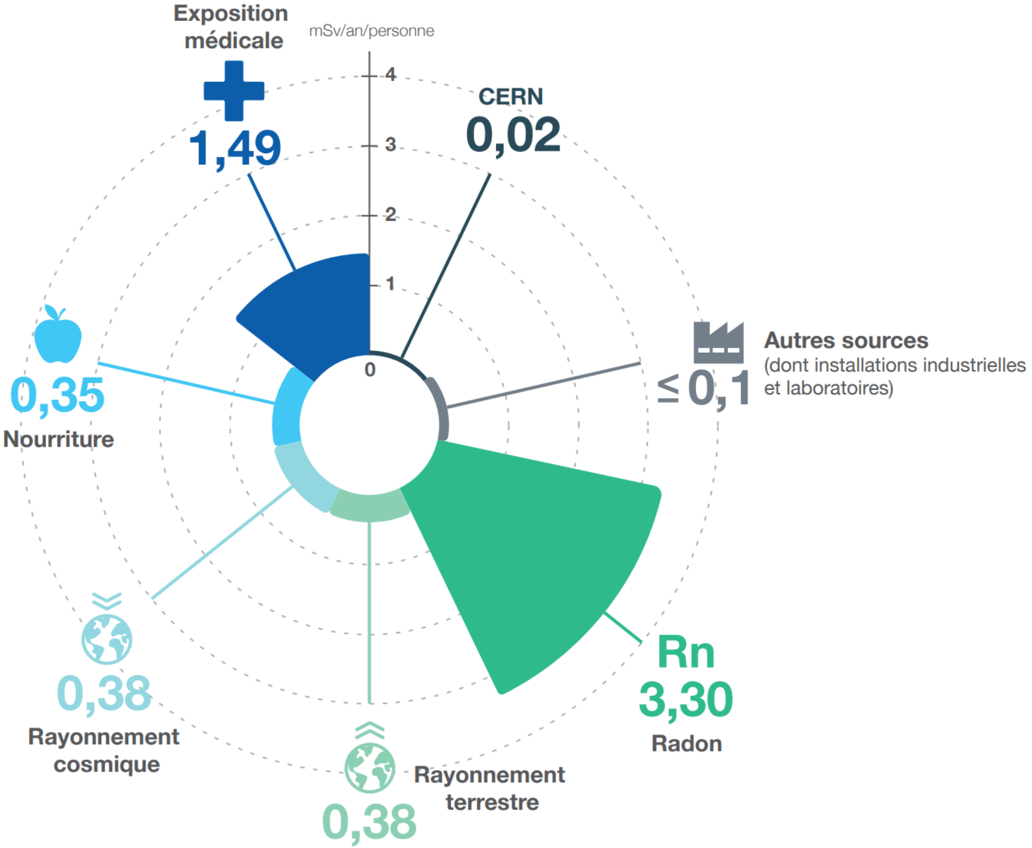


Réaction en chaine contrôlé

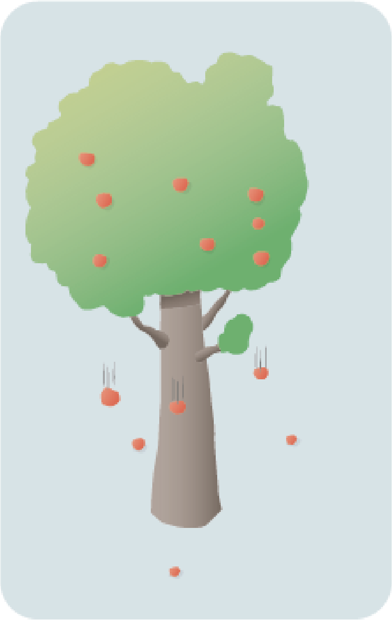


Doses de rayonnements

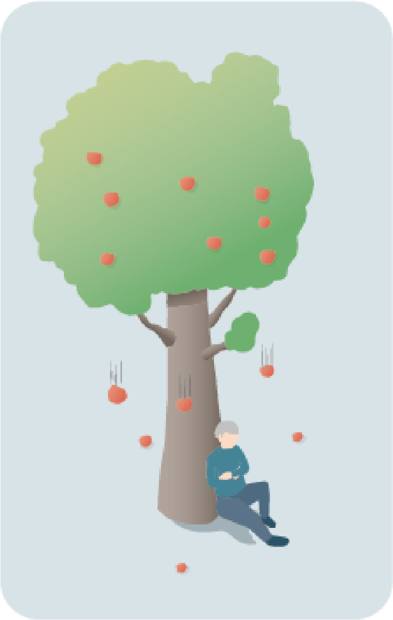
- Unité?



https://www.andra.fr/les-dechets-radioactifs/la-radioactivite/mesures-de-la-radioactivite



Le nombre de pommes qui tombent peut se comparer au **Becquerel** (nombre de désintégrations par seconde)



Le nombre de pommes reçues par le dormeur peut se comparer au **Gray** (dose absorbée)

L’effet laissé sur son corps selon le poids ou la taille des pommes peut se comparer au **Sievert** (effet produit)

https://www.universityofcalifornia.edu/sites/default/files/uc_climatechange_illustrations_banana-radiation.png

Flight from NY to LA

Long flights expose you to more radiation than airport security.

400 BANANAS
40 µSv

Living in a concrete stone, or brick building for a year

700 BANANAS
70 µSv

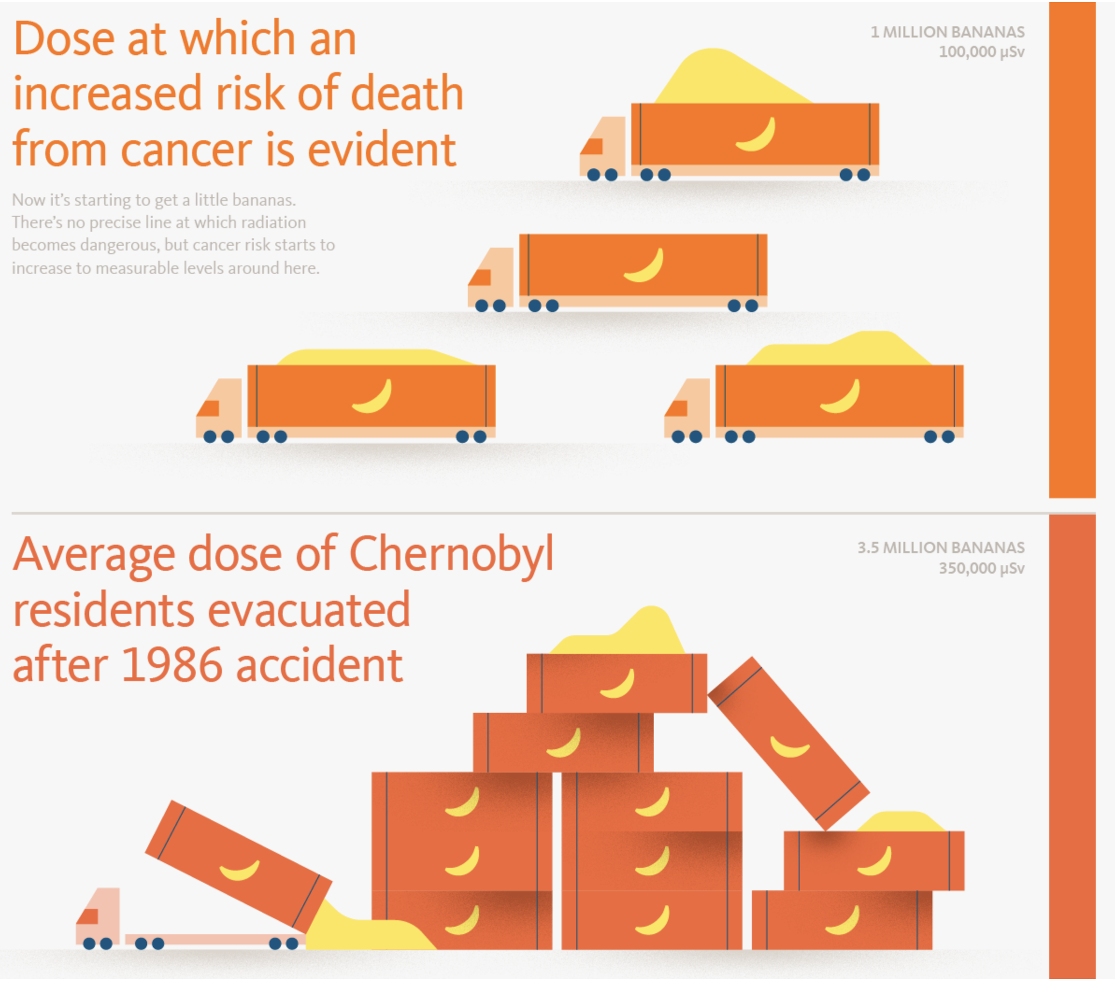
CT Scan

100,000 BANANAS
10,000 µSv

Smoking a pack of cigarettes a day for 1 year

240,000 BANANAS
24,000 µSv

Need another reason to quit?
Smoking a pack a day exposes you
to more radiation than everything
above put together.



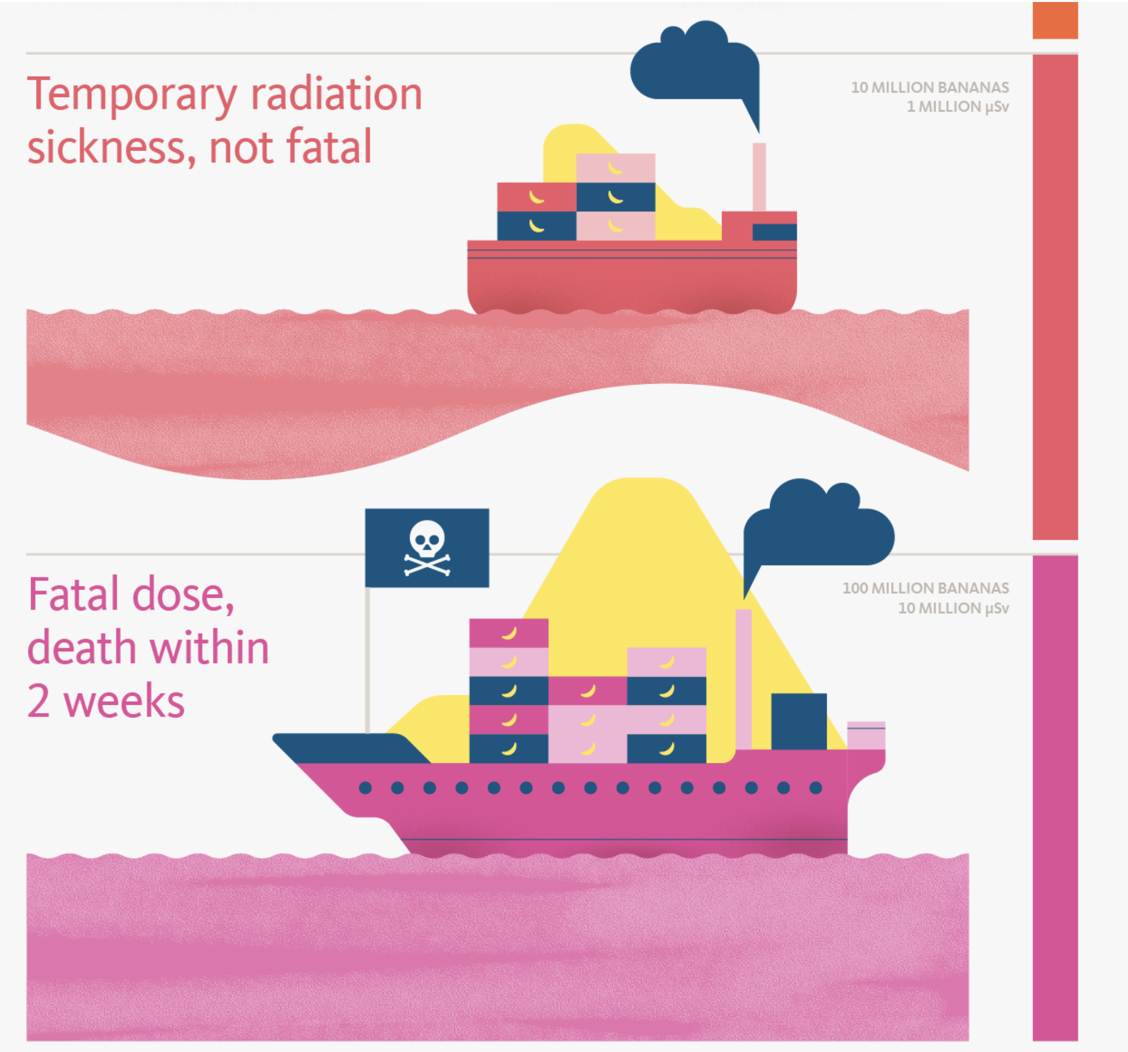
Dose at which an increased risk of death from cancer is evident

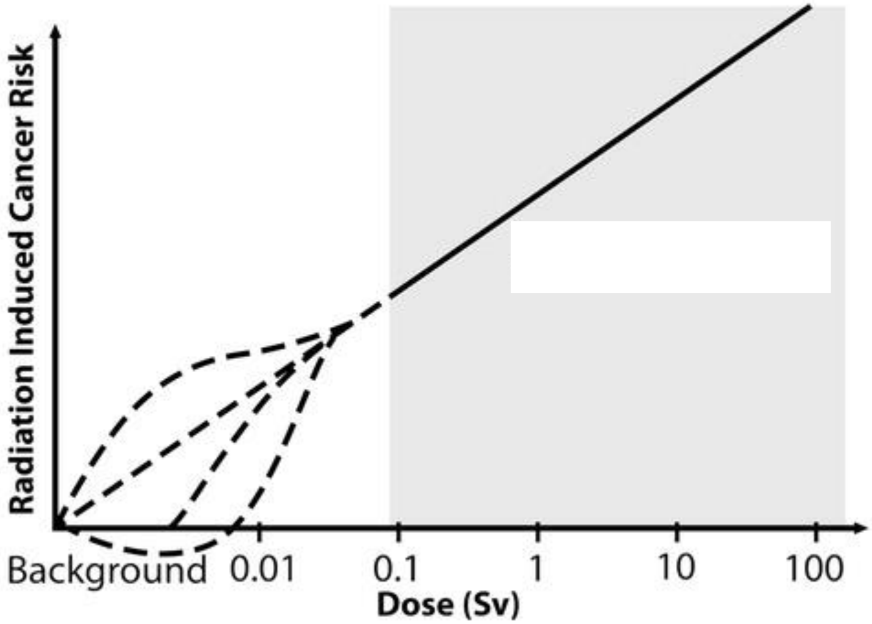
Now it's starting to get a little bananas. There's no precise line at which radiation becomes dangerous, but cancer risk starts to increase to measurable levels around here.

1 MILLION BANANAS
100,000 µSv

Average dose of Chernobyl residents evacuated after 1986 accident

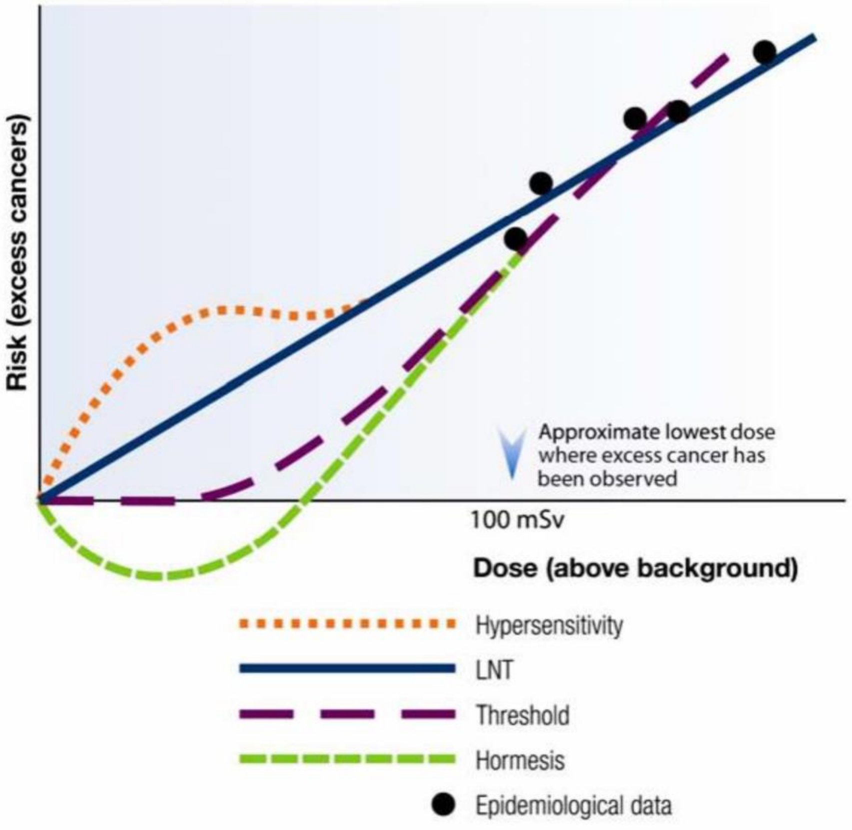
3.5 MILLION BANANAS
350,000 µSv


Temporary radiation sickness, not fatal
10 MILLION BANANAS
1 MILLION μSv
Fatal dose, death within 2 weeks
100 MILLION BANANAS
10 MILLION μSv



5 % / Sv

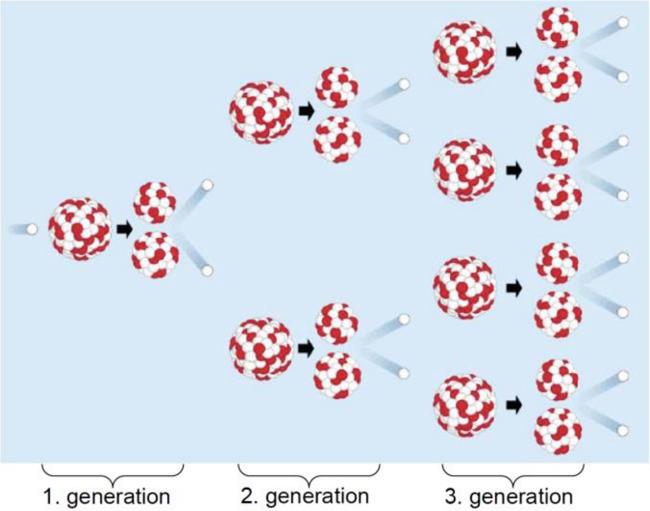
1 Sv = 10^7 🍌 = vivre 500 ans en suisse


Risk (excess cancers)
Approximate lowest dose where excess cancer has been observed
100 mSv
Dose (above background)
Hypersensitivity
LNT
Threshold
Hormesis
Epidemiological data

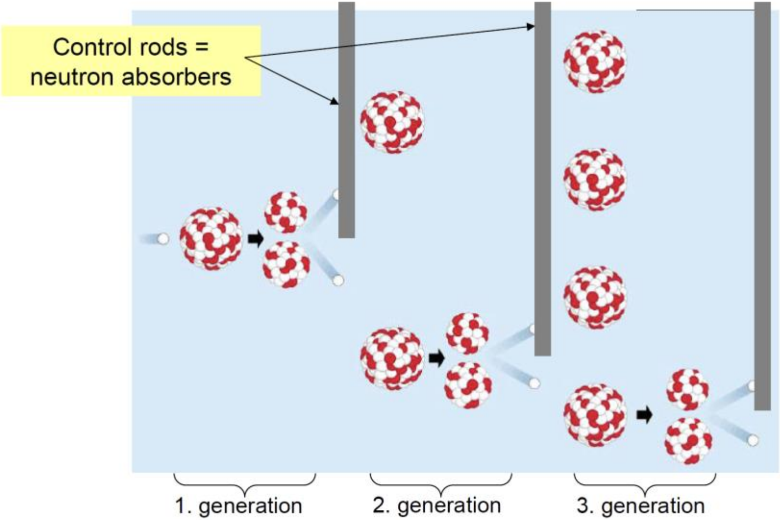
Visite CROCUS

Combien de bananes?

Réaction en chaine sans contrôle



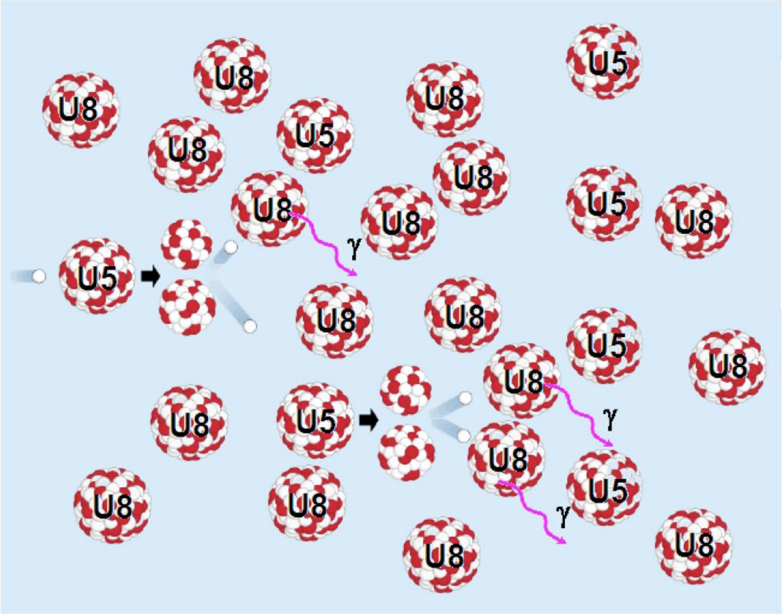
Réaction en chaine contrôlé



Isotope	Atom-%	relative Mass	half life period
U-234	0.0055	234.0410	245500 a
U-235	0.720	235.0439	$0.7038 \cdot 10^9$ a
U-238	99.274	238.0508	$4.468 \cdot 10^9$ a

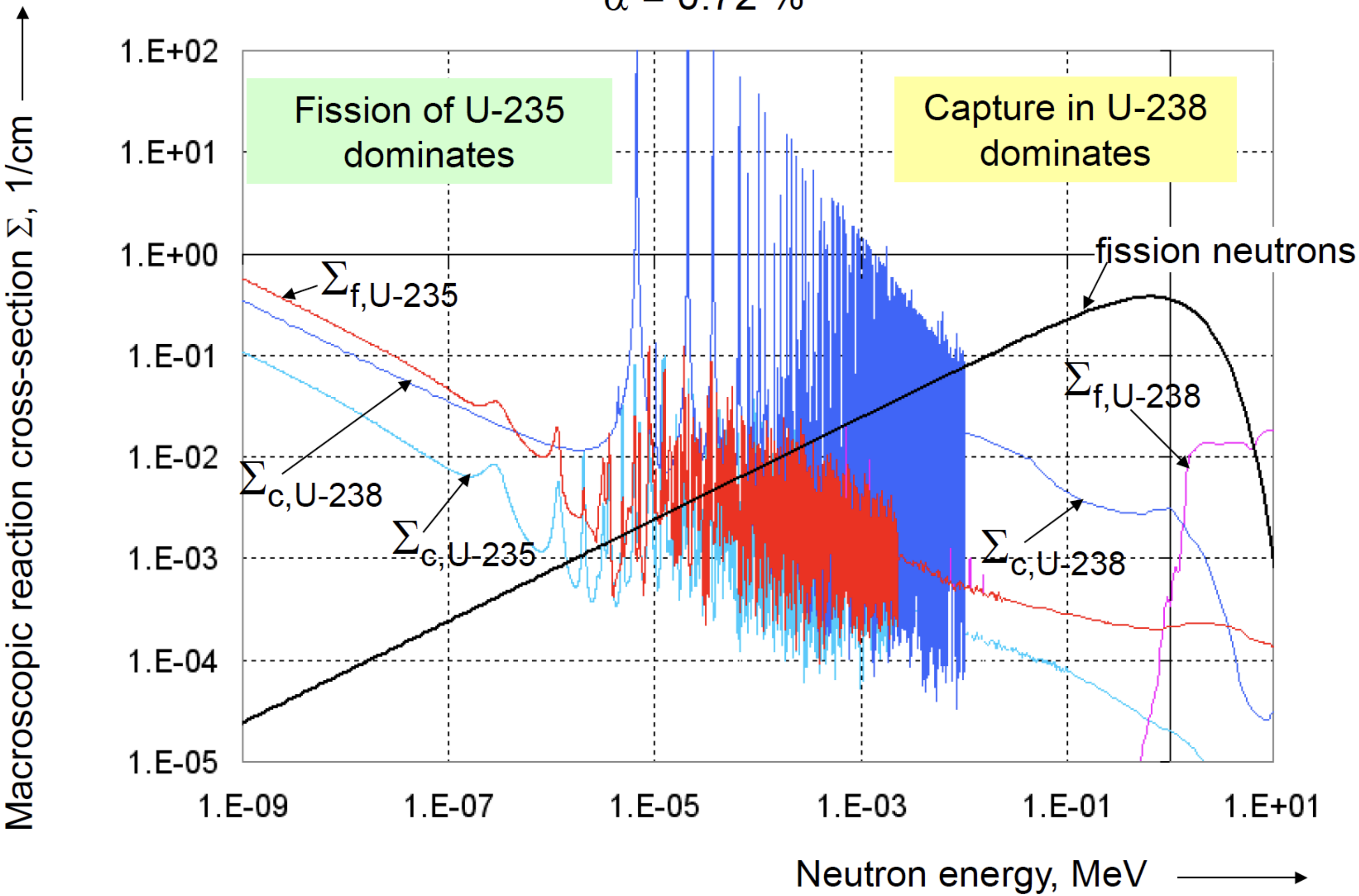
Fissile with thermal neutrons

Non-fissile, fissible only with sufficiently fast neutrons

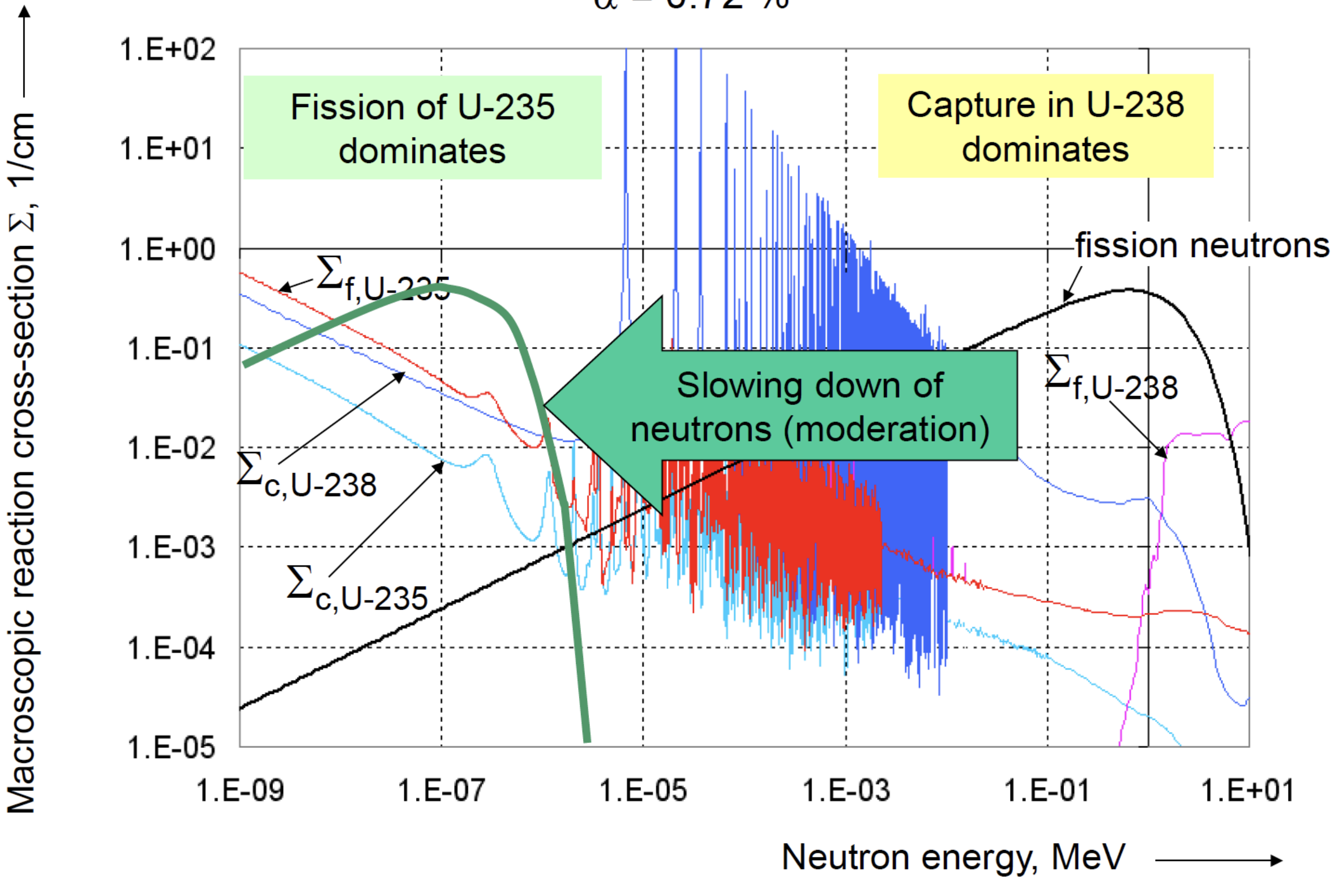


- U-238 dominates → most fission neutrons consumed by capturing in U-238
- Chain reaction with natural uranium alone is not feasible

α = 0.72 %

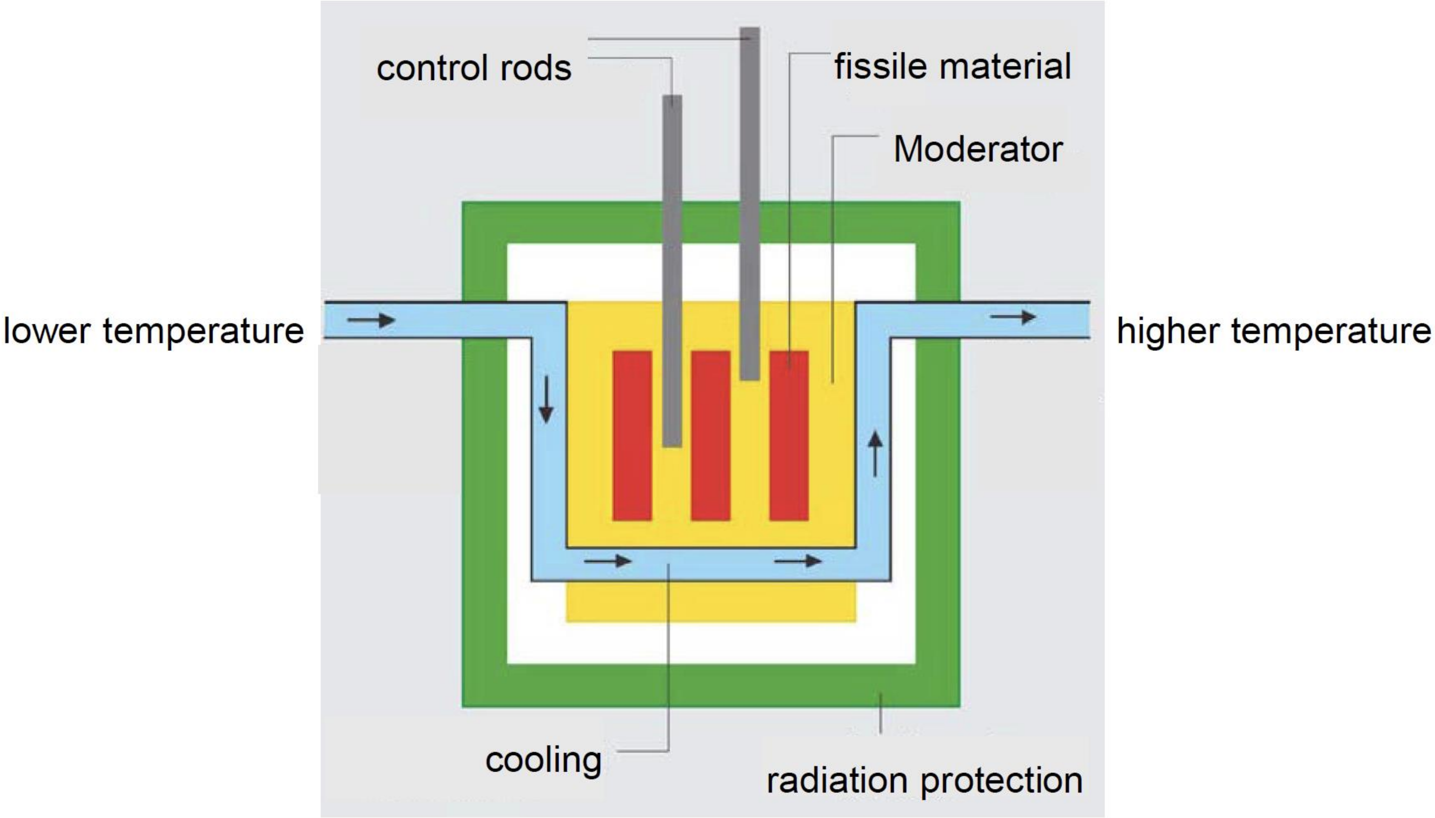

Macroscopic reaction cross-section Σ, 1/cm
Neutron energy, MeV
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-09
1.E-07
1.E-05
1.E-03
1.E-01
1.E+01
Fission of U-235 dominates
Capture in U-238 dominates
fission neutrons
$\Sigma_{f,U\text{-}235}$
$\Sigma_{c,U\text{-}238}$
$\Sigma_{c,U\text{-}235}$
$\Sigma_{f,U\text{-}238}$
$\Sigma_{c,U\text{-}238}$

α = 0.72 %



Moderation makes possible chain reaction at low U-235 content

Fundamental scheme of a reactor with thermal neutrons

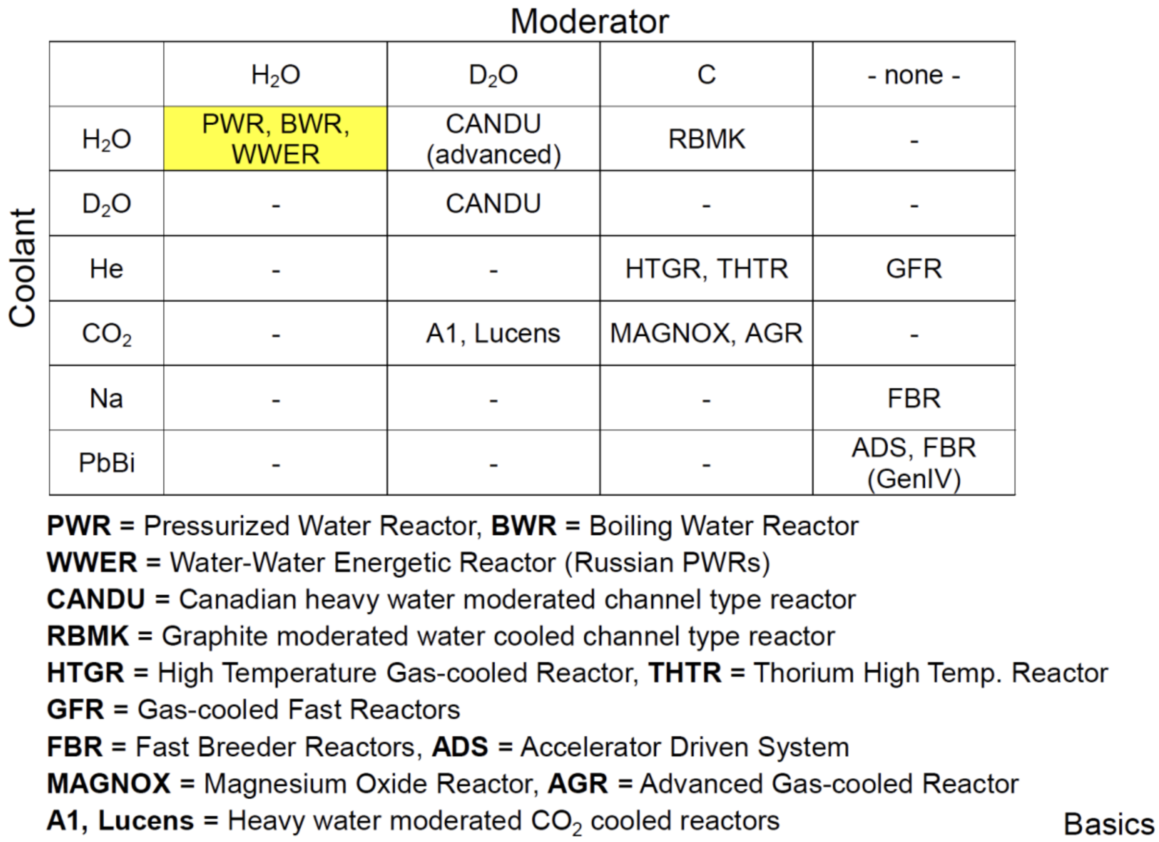


Le premier reacteur

Enrico Fermi: December 2, 1942

40 t U-nat
385 t Graphite

Power ~2 kW



Moderator

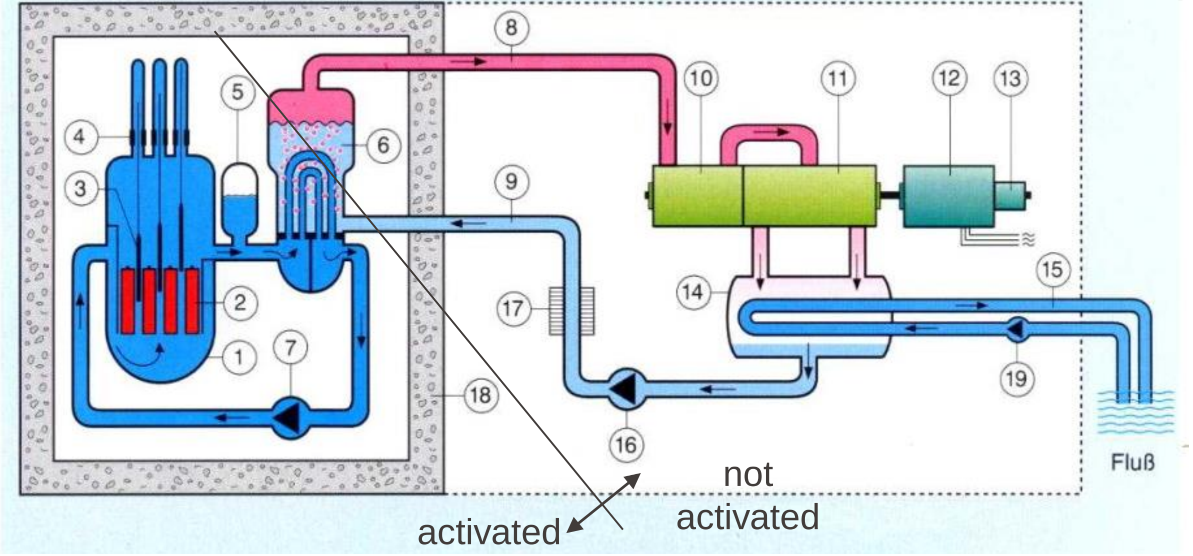
Coolant

	H_2O	D_2O	C	- none -
H_2O	PWR, BWR, WWER	CANDU (advanced)	RBMK	-
D_2O	-	CANDU	-	-
He	-	-	HTGR, THTR	GFR
CO_2	-	A1, Lucens	MAGNOX, AGR	-
Na	-	-	-	FBR
PbBi	-	-	-	ADS, FBR (GenIV)

PWR = Pressurized Water Reactor, **BWR** = Boiling Water Reactor
WWER = Water-Water Energetic Reactor (Russian PWRs)
CANDU = Canadian heavy water moderated channel type reactor
RBMK = Graphite moderated water cooled channel type reactor
HTGR = High Temperature Gas-cooled Reactor, **THTR** = Thorium High Temp. Reactor
GFR = Gas-cooled Fast Reactors
FBR = Fast Breeder Reactors, **ADS** = Accelerator Driven System
MAGNOX = Magnesium Oxide Reactor, **AGR** = Advanced Gas-cooled Reactor
A1, Lucens = Heavy water moderated CO_2 cooled reactors

Basics

General scheme of a Pressurized Water Reactor (PWR)



not activated

activated

1 - Reactor Pressure Vessel, 2 - Fuel Elements, 3 - Control Rods, 4 - Control rod drives,

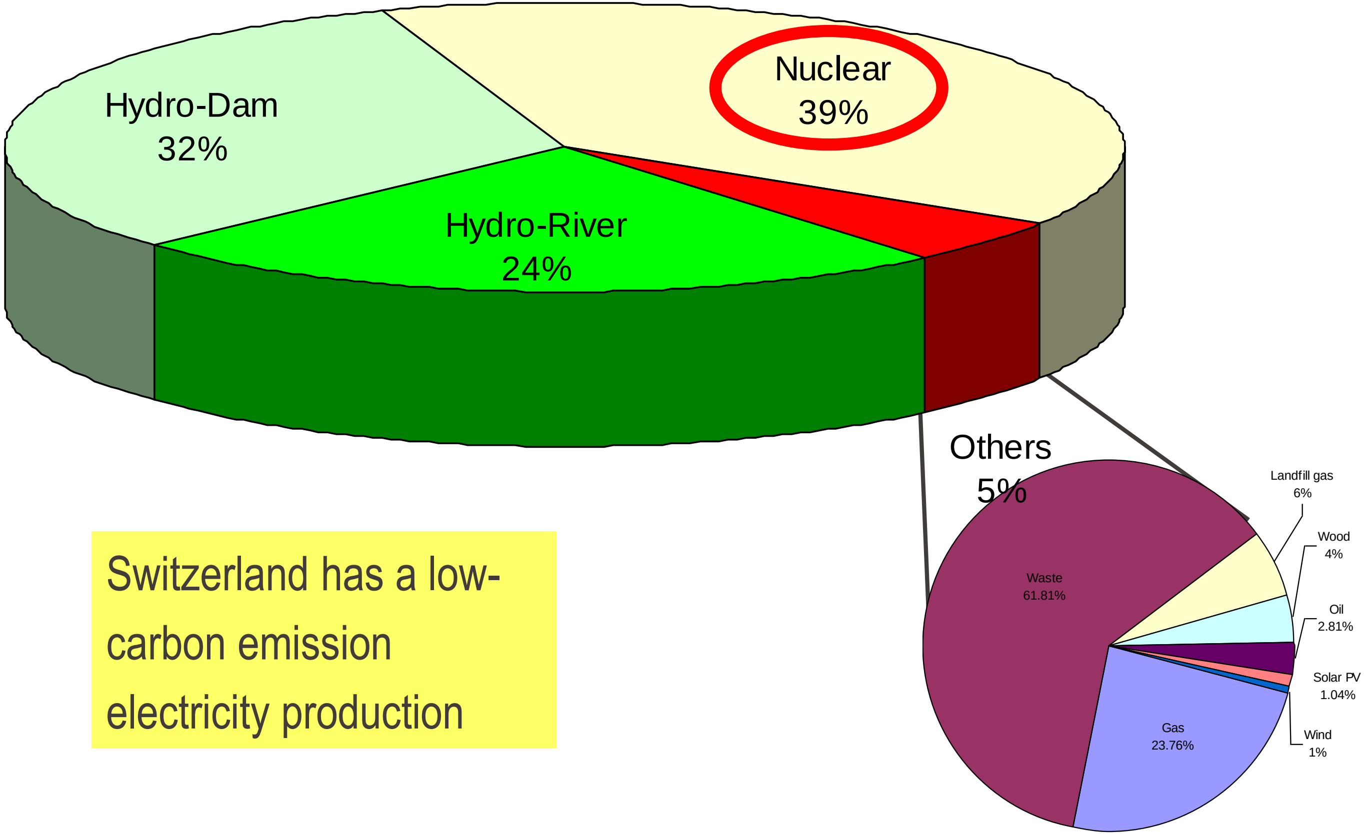
5 - Pressurizer, 6 - Steam Generator, 7 - Main Coolant Pump, 8 - Main Steam Line,

9 - Feed water line, 10 - High Pressure Stage of the Turbine, 11 - Low Pressure Stage,

12 - Generator, 13 - Exciter, 14 - Condenser, 15 - River Cooling, 16 - Feed water Pump,

17 - Regenerative Pre-Heater Stages, 18 - Concrete Shielding, 19 - Cooling Water Pump

Electricity Generation in Switzerland (2015)



Switzerland has a low-carbon emission electricity production

NPPs in Switzerland

1 MÜHLEBERG NUCLEAR POWER PLANT, 2 GÖSGEN NUCLEAR POWER PLANT, 3 LEIBSTADT NUCLEAR POWER PLANT, 4 BEZNAU NUCLEAR POWER PLANT, 5 PSI AND ZWILAG

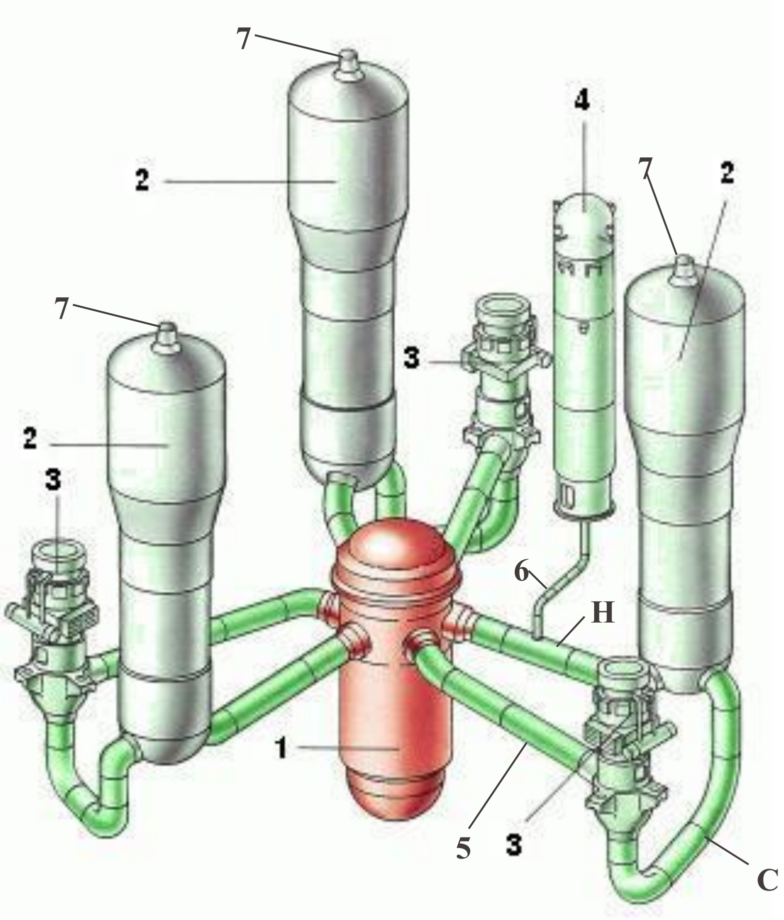
NPP	Type	Net Elect. Power
Beznau I	PWR	365 (MWe)
Beznau II	PWR	365 (MWe)
Mühleberg	BWR	373 (MWe)
Gösgen	PWR	1010 (MWe)
Leibstadt	BWR	1220 (MWe)

- Outlook (2017 votation)
  - No construction licenses will be issued for new NPP
  - Existing reactors allowed to operate as long as they are safe

Pressurizer vessel

Main circulation pump of a PWR

Primary circuit of a PWR



More than 1 loop needed to remove the thermal power

1 – Reactor

2 – Steam generator

3 – Main coolant pump

4 – Pressurizer

5 – Main coolant lines

6 – Pressurizer surge line

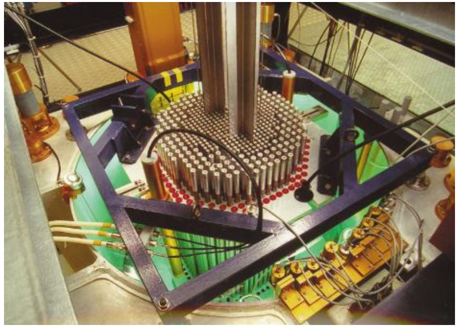
7 – Main steam nozzle

H – hot leg

C – cold leg

Example: Three-loop design (e.g. NPP Gösgen)

The CROCUS reactor



Reactor type

- LWR with partially submerged core
- Room T (controlled) and atmospheric P

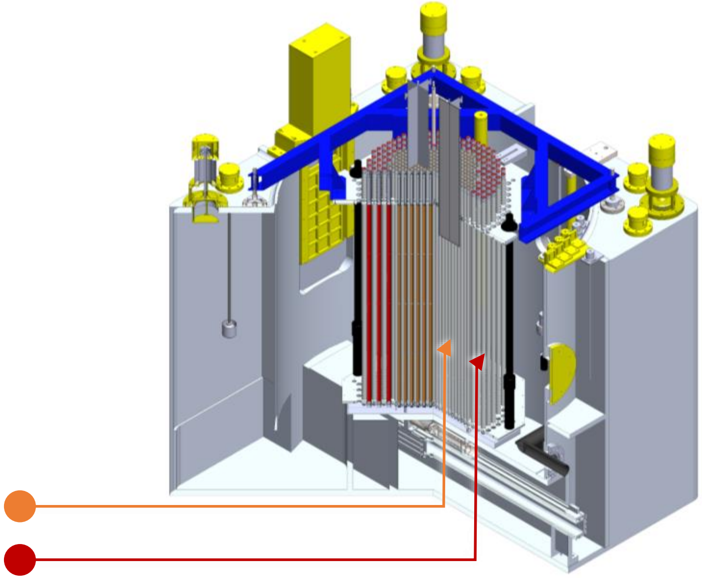
Operation

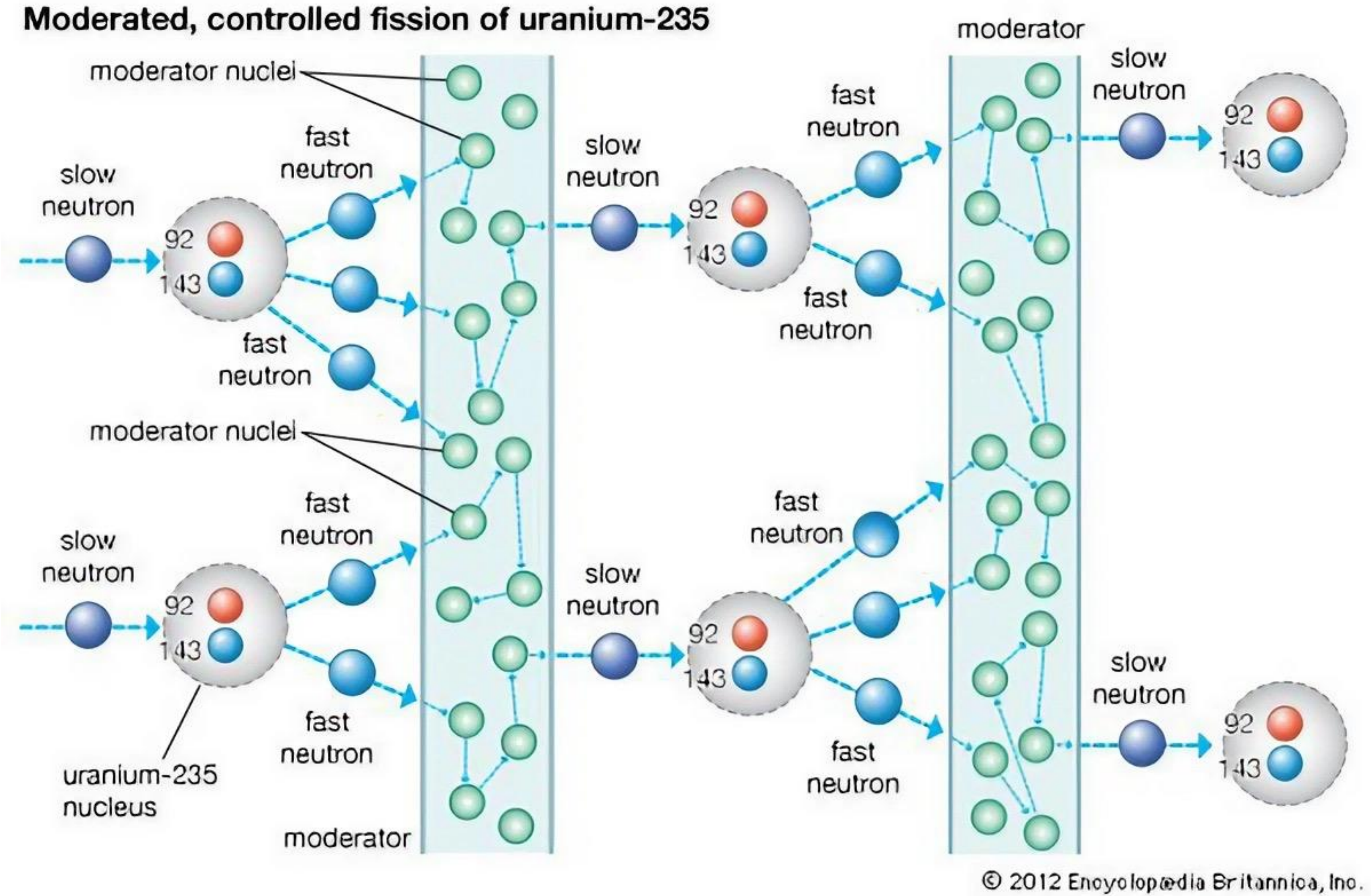
- 100 W (zero-power reactor)
- i.e. maximum 2.5×10^9 $cm^{-2}.s^{-1}$
- Control: B_4C rods and spillway

Core

- ⌀60 cm/100 cm, 2-zone

Inner:	336 UO_2	1.806 wt%	1.837 cm
Outer:	176 U_{met}	0.947 wt%	2.917 cm




Moderated, controlled fission of uranium-235
moderator nuclei
fast neutron
slow neutron
92
143
fast neutron
fast neutron
moderator nuclei
fast neutron
slow neutron
92
143
fast neutron
uranium-235 nucleus
moderator
slow neutron
92
143
fast neutron
fast neutron
slow neutron
fast neutron
92
143
fast neutron
moderator
slow neutron
92
143
slow neutron
92
143
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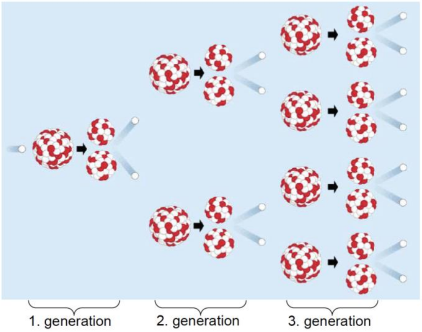
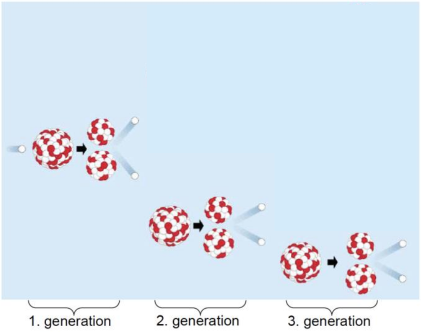
Approche critique

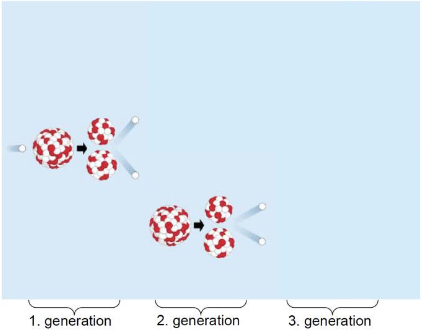
Facteur de multiplication $k = \frac{Production}{Fuites+Absorptions}$



k>1: sur-critique



k=1: critique

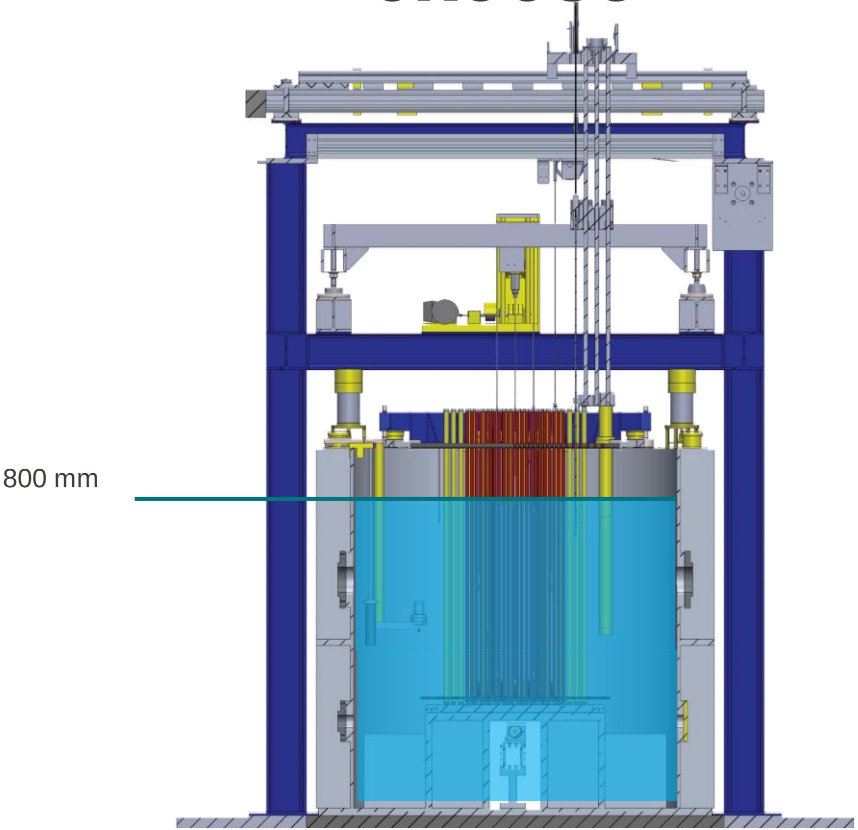


k<1: sous-critique

K↑ si on ajoute du:

- ^{235}U
- Moderateur (mais ca ne suffit pas tout seul..)

CROCUS



→ Niveau d'eau ∝ k

Réacteur stable k=1

Comment estimer le 'niveau d'eau critique'?

Merci !
Questions?